CU-TP-898

Baryon Number Transport via Gluonic Junctions

Stephen E. Vance, Miklos Gyulassy
Physics Department, Columbia University, New York, N.Y. 10027

Xin-Nian Wang
Nuclear Science Division, Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA 94720

(8 June 1998)

Abstract

A novel non-perturbative gluon junction mechanism is introduced within the HIJING/B nuclear collision event generator to calculate baryon number transport and hyperon production in pA and AA collisions. This gluonic mechanism can account for the observed large mid-rapidity valence baryon yield in $Pb + Pb$ at 160 AGeV and predicts high initial baryon densities at RHIC. However, the highly enhanced $\Lambda - \bar{\Lambda}$ yield and the baryon transverse momentum flow observed in this reaction can only be partially described.

Recent data [1–5] on $p + A$ and $A + B$ interactions at the CERN SPS has revealed a large degree of stopping and strange hyperon production in the heavy nuclear systems. The stopping is significantly under-predicted by models which assume that the primary mechanism for baryon transport is diquark-quark ($qq - q$) hadronic strings [6,7]. In this letter we implement a variant [8] of the baryon junction mechanism [9,10] to address this problem. This implementation is now available as a Monte Carlo event generator, HIJING/B [11], a new version of the HIJING model [12].

In Fig. 1, the rapidity distributions of valence protons and lambdas are compared to HIJING predictions. It is clear that even in $p+S$ reactions, the mid-rapidity baryon distribution is largely under-predicted. In HIJING, as in the LUND Fritiof [13] and dual parton model (DPM) [14], the valence baryons cannot move inward from the beam and target fragmentation regions by more than about 2 units of rapidity because of the assumed diquark fragmentation dynamics of the $qq - q$ strings.

Several models have considered additional mechanisms or string configurations to correct this problem. In the VENUS model [15], the stopping and strange baryon production is reproduced by adding an *ad hoc* double string mechanism whose parameters are adjusted to fit the data. The RQMD [16] and UrQMD [17] event generators reproduce the observed stopping through incoherent multiple inelastic scattering of the valence (di)quarks. The difficulty with this idea is that the time dilation of inelastic processes at high energies leads to coherence which is absent in this model.

In a new version of the DPM model [18], enhanced baryon stopping is more naturally achieved by introducing a diquark breaking mechanism [10]. In this approach, a gluon exchange mediates the break-up of the diquark by changing its color state from a $\{\bar{3}\}$ to a $\{6\}$. The cross section for this interaction is then estimated [10] to be

$$\frac{d\sigma}{dy}(ph \to pX) \approx C \left(\frac{1GeV}{\sqrt{s}}\right)^{1/2} \cosh(y/2), \tag{1}$$

where $C \simeq 7$ mb was estimated to fit the observed baryon stopping in pp collisions at the ISR [10]. The unusual $\cosh(y/2)$ rapidity dependence and $1/\sqrt[4]{s}$ energy dependence follow here from the Regge motivated $1/\sqrt{x}$ distribution of the valence quarks in the proton at small x. The resulting configuration is a $q - q - q$ string where the baryon number is associated with the middle quark. In nucleus-nucleus collisions, diquarks are assumed to remain broken once they transform into a $\{6\}$ color state. Thus, in $A + B$ collisions, the probability for diquark breaking should be $P_{DB}^{AB} = 1 - (1 - P_{DB}^{NN})^n$, where n is the number of collisions and P_{DB}^{NN} is the diquark breakup probability in a nucleon-nucleon collision. For a heavy nucleus, very few of the diquarks survive. The addition of this diquark breaking component was shown in [18] to reproduce the observed stopping in AA collisions at the SPS. However, this mechanism alone could not account for the observed strangeness enhancement without including additional final state interaction effects [19].

In this letter, we consider another Regge motivated mechanism [9] which also leads to eq. (1) but which differs from the diquark breaking model in multiplicity and strangeness enhancements. This mechanism is motivated from the non-perturbative gluon field configuration (the baryon junction) that appears when writing the simplest gauge invariant operator for the baryon in $\mathrm{SU}_c(3)$;

$$
\begin{aligned}
B = \epsilon^{j_1 j_2 j_3} & \left[P \exp\left(ig\int_{x_1}^{x_J} dx^\mu A_\mu\right) q(x_1)\right]_{j_1} \left[P \exp\left(ig\int_{x_2}^{x_J} dx^\mu A_\mu\right) q(x_2)\right]_{j_2} \\
\times & \left[P \exp\left(ig\int_{x_3}^{x_J} dx^\mu A_\mu\right) q(x_3)\right]_{j_3} .
\end{aligned} \tag{2}
$$

Here, the baryon junction is the vertex at x_J where the three gluon Wilson lines link the three valence quarks to form the gauge invariant non-local operator. In a highly excited baryonic state, the Wilson lines represent color flux tubes. When these strings fragment via $q\bar{q}$ production, the resulting baryon will be composed of the three sea quarks which are linked to the junction while the original valence quarks will emerge as constituents of three leading mesons. Being a gluonic configuration, it was proposed [8] that the junction could be more easily transported into the mid-rapidity region in hadronic interactions.

In Regge phenomenology, allowing for the possibility of baryon junction exchanges in pp and $p\bar{p}$ scattering is taken into account by adding new Regge trajectories (M^J). Here, the exchange of the leading M_0^J trajectory is characterized by a three jet event in contrast to the two jet event resulting from the Pomeron exchange. Phenomenologically, the difference between the $p\bar{p}$ and pp topological cross sections, $\Delta\sigma = \sigma(p\bar{p}) - \sigma(pp)$, is given by the contributions of the ρ, ω and M_0^J Regge exchanges [9]. Analysis of the energy dependence and the multiplicity distributions of pp and $p\bar{p}$ data shows that $\Delta\sigma \propto s^{-1/2}$ [20] and that the difference, $\Delta\sigma$, may be largely associated with annihilations [21]. Upon associating $\Delta\sigma$ with the annihilations or the M^J exchanges, the intercept of the leading term, $\alpha_{M_0^J}(0)$, can be estimated from the energy dependence of $\Delta\sigma$, i.e. $\Delta\sigma \propto s^{-1/2} \simeq s^{1-\alpha_{M_0^J}(0)}$, giving $\alpha_{M_0^J}(0) \simeq 1/2$. This value of $\alpha_{M_0^J}(0) \simeq 1/2$ is also consistent with estimates of the intercept using multi-peripheral model approximations [22,9]. In addition, various models which associated $\Delta\sigma$ with three sheet, M_0^J type annihilation events were able to explain the observed mean multiplicity, $\bar{n}_{B\bar{B}ann} \simeq \frac{3}{2}\bar{n}_{B\bar{B}scatt}$ [9], the observed multiplicity distributions of $\Delta\sigma$ [23], and the experimental values of the ratio $R_n = (\sigma(p\bar{p})_n - \sigma(pp)_n)/\sigma(pp)_n$, where n is the prong number [20]. Recently, Kharzeev [8] used the exchange of the M_0^J Reggeon in baryon production to propose a new baryon stopping mechanism. This mechanism is able account for the excess of mid-rapidity valence baryons in pp at ISR energies and was suggested to provide substantial stopping at RHIC and the LHC. In this letter, we implement this new baryon stopping mechanism into the Monte Carlo event generator HIJING/B, and tests its implications for RHIC.

As was shown by Kharzeev [8], the energy and rapidity dependence of the inclusive baryon production at mid-rapidity can be obtained using Mueller's generalized optical theorem [24] in the double Regge limit. Here, the exchanges of a Pomeron and a M_0^J Reggion lead to the following form for single mid-rapidity baryon production,

$$
E_B \frac{d^3\sigma^{(1)}}{d^3 p_B} = C_B f_B(m_t^2) \left(\frac{s_0}{s}\right)^{1/4} \cosh(y/2) \ . \tag{3}
$$

where C_B is a constant that reflects the couplings of the Reggeon and Pomeron to the proton, $f_B(m_t^2)$ is an unknown function of m_t and $s_0 \simeq 1$ GeV is a Regge energy scale. The $\cosh(y/2)$ rapidity dependence and the $1/\sqrt[4]{s}$ energy dependence follow from the assumed intercept, $\alpha_{M_0^J}(0) \approx 1/2$. In contrast to the diquark breaking model in the DPM, the multiplicity [8]

of these events is enhanced by a factor of 5/4 while the strangeness content is enhanced by a factor of 3. The enhancement factor of 3 of the strangeness content of the baryon allows for the unique possibility of producing $S = -3$ Ω^- baryons.

We note that the value of the junction intercept, $\alpha_{M_0^J}(0) = 1/2$, has been criticized by the authors of the diquark breaking mechanism [25]. Following the phenomenology which motivated the diquark breaking mechanism, they show that the exchange of two gluons in the $\{10\}$ color state (Decameron) leads to baryon number transport with baryon junctions. However, in contrast to the above model using the exchange of M^J Reggeons, their model leads to a constant, energy independent annihilation cross section [25], $\sigma_{\{10\}} \simeq 1-2$ mb, and a uniform, rapidity independent, inclusive cross section for mid-rapidity baryon production [10], $d\sigma(pp \rightarrow pX)/dy \simeq 0.1$ mb. They also fit [25] the multiplicity distributions of $\Delta\sigma$ at $E_{lab} = 10, 20, 50$ and 100 GeV to argue that $\Delta\sigma$ is dominated by the ρ and ω exchanges, while the three sheet annihilation component only contributes a small energy independent cross section of $1-2$ mb. The energy dependence of this small three sheet annihilation cross section would then imply that $\alpha_{M_0^J}(0) \simeq 1$.

In HIJING/B [11], we implement Kharzeev's [8] model through a "Y" string configuration for the excited baryon. For reactions without junction exchange, standard $qq-q$ strings are used. The baryon is resolved around the junction via $q\bar{q}$ production and the resulting three beam jets are fragmented as $q-\bar{q}$ strings. The hard processes are modeled as kinks in one of the three $q\bar{q}$ strings. A value of $\sigma_{BJ} = 18$ mb is taken to reproduce valence proton data [26] from $p+p$ collisions at 400 GeV/c incident momentum ($\sqrt{s_0} = 27.4$ GeV). In order for the three beam jets to have sufficient phase space to decay, the junction exchange is only allowed if the invariant mass of the excited "Y" configuration exceeds $m \geq 5$ GeV. At SPS energies, this kinematic constraint considerably limits the number of junction exchanges allowed, reducing its effective cross section to ~ 9 mb. Like the modified DPM, we assume for multiple collisions that the baryon junction remains stopped in subsequent soft interactions once it has been exchanged. The $\vec{p}_T$ of the junction baryon is obtained by adding the $\vec{p}_T$ of the three sea quarks. We note that the present version of HIJING/B does not include final state interactions, as our main interest is to test the extent to which initial state non-equilibrium dynamics can account for the observed strangeness and $p_\perp$ enhancements.

In Fig 1, the valence proton rapidity ($dN/dy_p - dN/dy_{\bar{p}}$) and valence hyperon rapidity ($dN/dy_\Lambda - dN/dy_{\bar{\Lambda}}$) distributions of HIJING and HIJING/B are compared with minimum bias $p+S$ data [1,2] at 200 AGeV and central $Pb+Pb$ (published and preliminary) data at 158 AGeV [3,5]. While HIJING severely under-predicts both the observed stopping and the hyperon production, the junction physics of HIJING/B sufficiently enhances both the baryon stopping and the hyperon production at mid-rapidity, reproducing the $p+S$ results. However, as seen in Fig 1d, even with the sizeable strangeness enhancement factor of 3, this gluonic mechanism can only partially account for the observed hyperon enhancement in the heavy systems such as $Pb+Pb$.

The p_T distributions of the protons are calculated in HIJING/B for $p+Pb$ at beam momenta of 450 GeV/c and $S+Pb$ at beam momenta of 200 GeV/c in the rapidity interval, $2.3 < y < 2.9$. The m_T distributions were then fit for $m_T - m_p < 0.68$ GeV with the functional form $Ed^3N/dp^3 = A\exp(-m_T/T)$, where A is a normalization constant and T is the inverse slope. The inverse slopes were found to be $T \approx 151$ MeV for $p+Pb$ and $T \approx 168$ MeV for $S+Pb$. The measured values from the NA44 collaboration [4] are $T = 195 \pm 5$

MeV for $p + Pb$ and $T = 256 \pm 4$ MeV for $S + Pb$. Although the $< p_T^2 >$ of the junction baryons is enhanced by the a factor of 3 over the normal $qq - q$ string, the contribution from this mechanism alone is insufficient to reproduce the observed enhanced flow. This results from the competition between the different p_T distributions which arise from the different production mechanisms. If one-half of the protons emerge from $qq - q$ strings where $T_{dq} \approx 130$ MeV, while the other one-half come from junction configurations where $T_{BJ} = \sqrt{3}T_{dq} \approx 225$ MeV, the effective inverse slope is only $T_{eff} \approx 173$ MeV in the measured region. The inability of this rather strong initial state non-equilibrium dynamical mechanism along with the already included Cronin effect to account for the observed transverse baryon flow provides evidence for its possible origin as due to final state interactions. We note also that the above junction dynamics alone provides no mechanism to account for the observed enhancement of the anti-proton p_T [4].

The impact parameter dependence of this stopping mechanism is studied in Fig 2 for the net valence baryons, $B - \bar{B} = (p - \bar{p}) + (n - \bar{n}) + (\Lambda - \bar{\Lambda})$. For the impact parameters $b = 0 - 3$ fm, $b = 4 - 5$ fm and $b = 7 - 8$ fm, a strong to moderate degree of baryon stopping is observed. However, at $b = 10 - 11$ fm, the degree of stopping has decreased and the shape suggests semi-transparency. Recent data [27] has shown the suppression of J/Ψ for impact parameter of $b \leq 8$ fm. Measurements of the impact parameter (E_T) dependence of baryon stopping would be of interest to test if the anomalous J/ψ suppression [27] threshold at $b \sim 8$ fm is correlated with the onset of greater baryon stopping. In the baryon junction exchange picture, a large degree of stopping is directly correlated with an enhanced gluonic field intensity at mid-rapidity that could partially be the cause of the ionization of $c - \bar{c}$ pairs.

The predictions of this model for the valence proton and lambda rapidity distributions in $Au + Au$ collisions at RHIC energies ($\sqrt{s} = 200$ GeV) are shown in Fig 3. HIJING/B predicts approximately twice the initial number of valence protons and five times the initial number of valence hyperons of HIJING at mid-rapidity leading to a prediction of twice the initial baryon density, $\rho(\tau_0) \approx 2\rho_0 \approx 0.3/\mathrm{fm}^3$. Previous predictions for RHIC assuming idealized zero baryon chemical potential scenarios should therefore be re-examined.

I. ACKNOWLEDGMENTS

We would like to thank D. Kharzeev, P. Jacobs and B.Z. Kopeliovic for stimulating and critical discussions.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract No. DE-FG02-93ER40764 and DE-AC03-76SF00098.

REFERENCES

[1] T. Alber et. al., (NA35 Collaboration), Z. Phys. **C64** (1994) 195.
[2] T. Alber et. al., (NA35 Collaboration), Eur. Phys. J. **C2** (1998) 643.
[3] I.G. Bearden et al., (NA44 Collaboration), Phys. Lett. **B388** (1996) 431.
[4] K. Wolf et al., (NA44 Collaboration), Phys. Rev. **C57** (1998) 837.
[5] G. Roland et al., (NA49 Collaboration), Proceedings of the Thirteenth International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions, Quark Matter '97.
[6] M. Gyulassy, V. Topor Pop, and S.E. Vance, Heavy Ion Physics **5** (1997) 299.
[7] V. Topor Pop, et al., Phys. Rev. **C52** (1995) 1618; M. Gyulassy, V. Topor Pop, X. N. Wang, Phys. Rev. **C54** (1996) 1497.
[8] D. Kharzeev, Phys. Lett. **B378** (1996) 238. nucl-th/9602027.
[9] G.C. Rossi and G. Veneziano, Nucl.Phys. B123 (1977) 507; Phys. Rep. **63** (1980) 153.
[10] B.Z. Kopeliovich and B.G. Zakharov, Z. Phys. C, **43**, (1989) 241.
[11] HIJING/B available upon request from svance@nt3.phys.columbia.edu.
[12] X. N. Wang and M. Gyulassy, Phys. Rev. **D44** (1991) 3501; Phys. Rev. **D45** (1992) 844; Comp. Phys. Comm. **83** (1994) 307 .
[13] B. Andersson, et al., Nucl. Phys. **B281** (1987) 289; Comp. Phys. Commun. **43** (1987) 387.
[14] A. Capella, U. Sukhatme, C. I. Tan and J. Tran Thanh Van, Phys. Rep. **236** (1994) 225.
[15] K. Werner, Phys. Rep. **232** (1993) 87.
[16] H. Sorge, Phys. Rev. **C52** (1995) 3291; nucl-th/9509007.
[17] S.A. Bass, et al., Prog. Part. Nucl. Phys. **41** (1998) 225; nucl-th/9803035.
[18] A. Capella, B.Z. Kopeliovich, Phys. Lett. **B381** (1996) 325; hep-ph/9603279.
[19] A. Capella, Phys. Lett. **B387** (1996) 400; hep-ph/9605216.
[20] L. Camilleri, Phys. Rep. **144**, (1987) 51.
[21] H.I. Miettinen, Rapporteur's talk, 3rd European Symposium on Antinucleon-Nucleon Reactions, Stockholm, 1976.
[22] Y. Eylon and H. Harari, Nucl. Phys. **B80** (1974) 349.
[23] B.R. Webber, Nucl. Phys. **B117** (1976) 445.
[24] A.H. Mueller, Phys. Rev. **D2** (1970) 2963.
[25] B.Z. Kopeliovich and B.G. Zakharov, Phys. Lett. **B211** (1988) 221.
[26] M. Aguilar-Benitez et al. (LEBC-EHS Collaboration), Z. Phys. **C50** (1991) 405.
[27] M. Gonin (NA50 Collaboration), Proc. of the Quark Matter '96 Conf., Eds. P. Braun-Munzinger et al., Nucl. Phys. **A610** (1996) 404c.

FIGURES

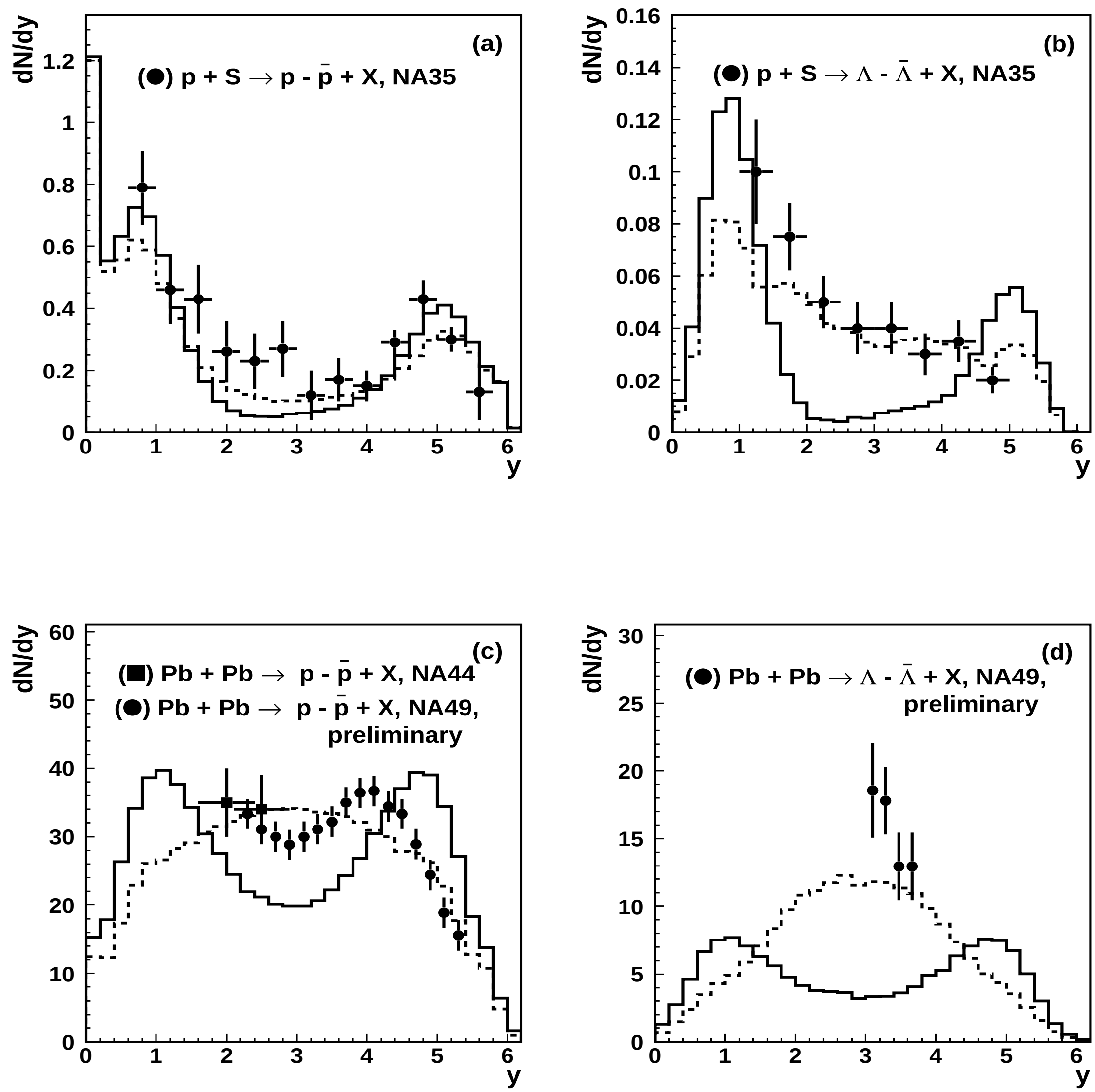

FIG. 1. HIJING (solid) and HIJING/B (dashed) calculations of the valence proton and hyperon rapidity distributions are shown for minimum bias $p+S$ collisions at 200 AGeV and central $Pb+Pb$ collisions at 160 AGeV. The data are from measurements made by the NA35 [1,2], NA44 [3] and NA49 [5] collaborations.

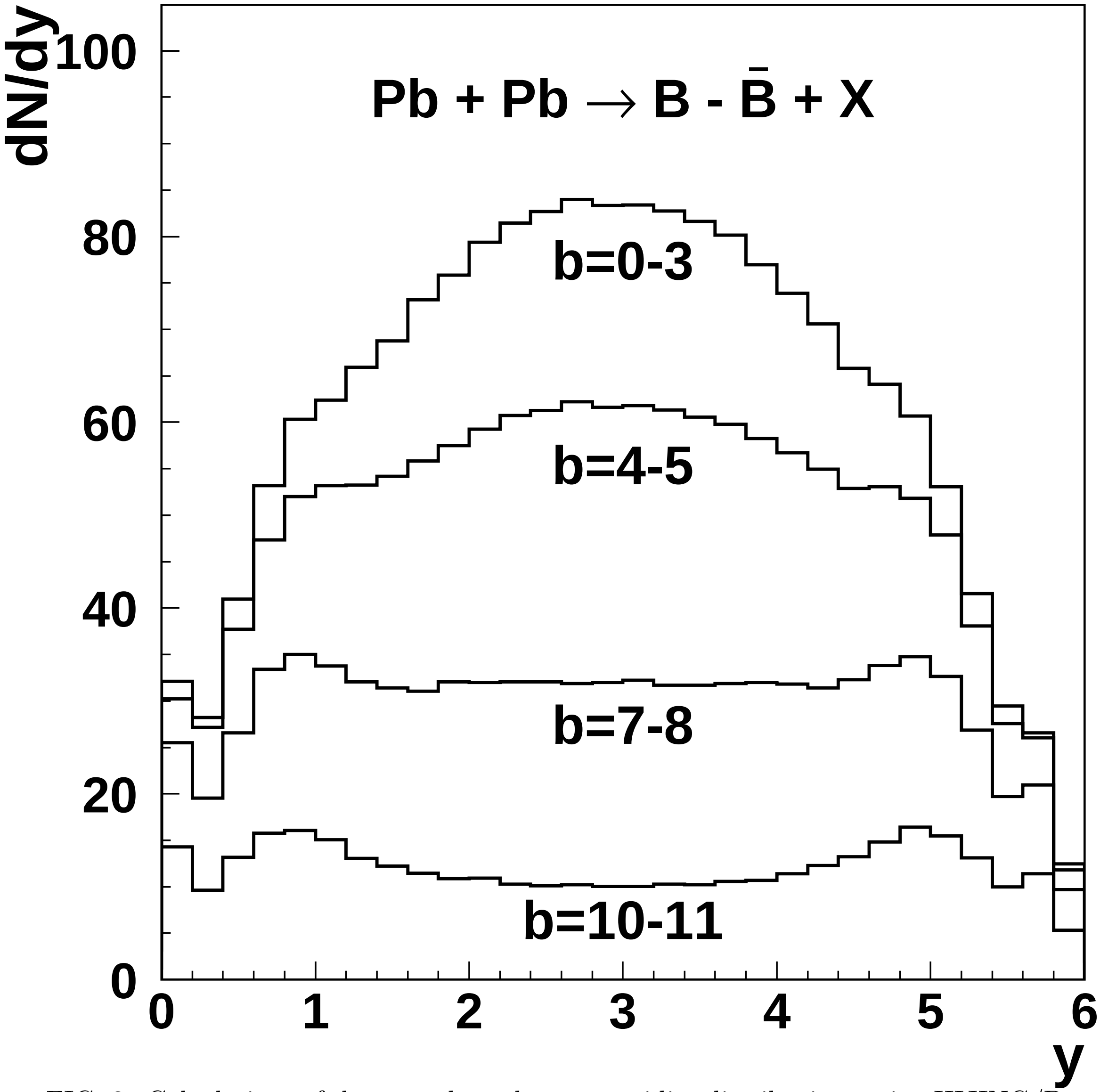

FIG. 2. Calculations of the net valence baryon rapidity distributions using HIJING/B are given for the impact parameter windows of $b = 0-3$ fm, $b = 4-5$ fm, $b = 7-8$ fm and $b = 10-11$ fm. In this calculation, the net valence baryons are defined as $B - \bar{B} = (p - \bar{p}) + (n - \bar{n}) + (\Lambda - \bar{\Lambda})$.

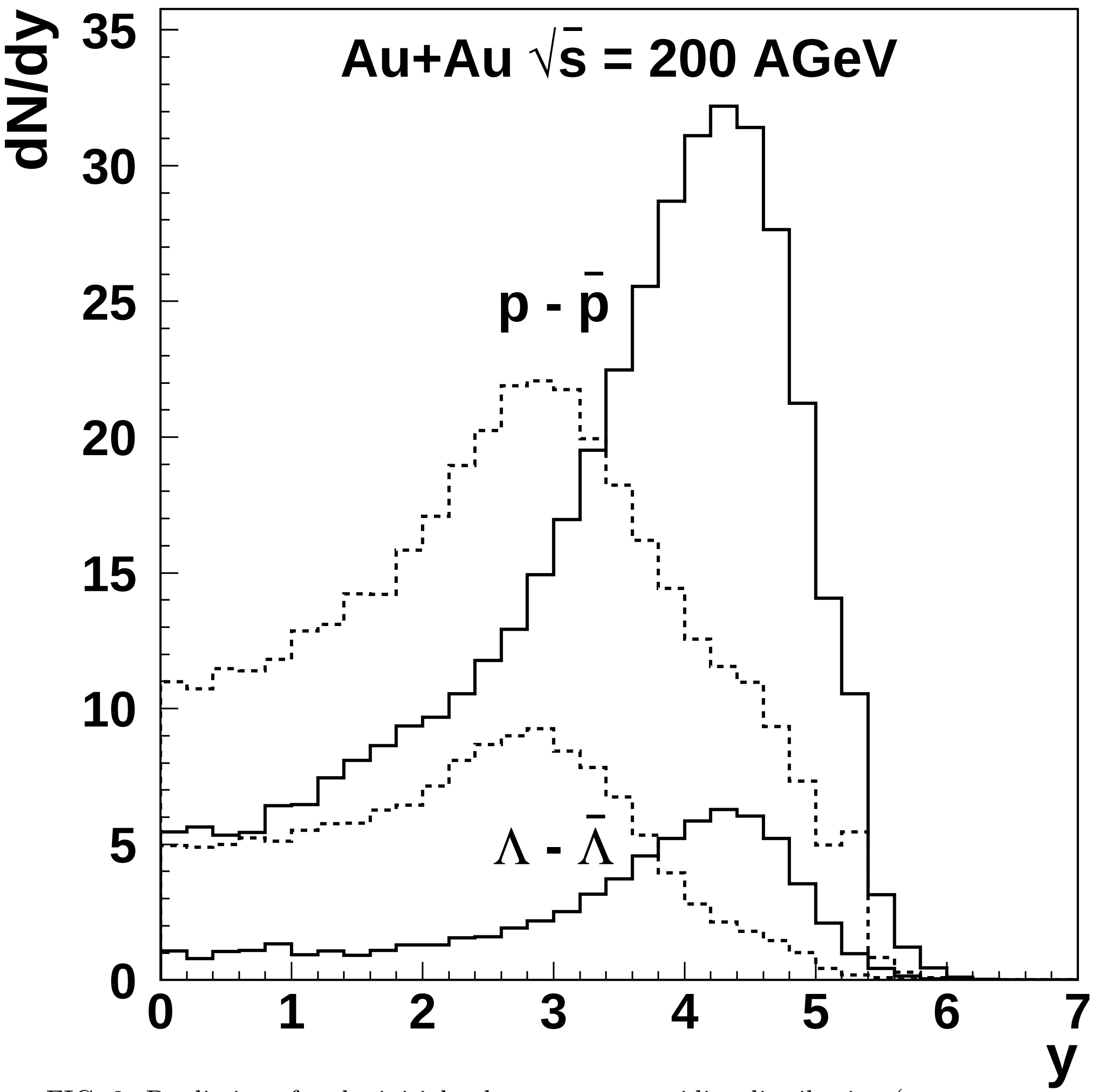

FIG. 3. Predictions for the initial valence proton rapidity distribution (upper two curves) and for the initial valence hyperon rapidity distribution (lower two curves) are given for Au+Au collisions at $E_{cm} = 200$ AGeV by HIJING (solid) and HIJING/B(dashed).